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Nanoscale magnetostrictive response in a thin film owing to a local magnetic field

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Scanning probe microscope experiments are presented in which thin magnetostrictive films deposited on top of micrometer-sized magnetic write heads as used in magnetic hard disk drives, are used to visualize their emanating magnetic field. The magnetostrictive expansion owing to magnetic writing fields is discussed, together with the transduction mechanisms that lead to the vertical and lateral contrast observed. Experimental results verify that the techniques described have a lateral resolution in the realm of 100 nm. © 2000 American Institute of Physics. [S0003-6951(00)02705-4]

Magnetic read-write heads (RWHs) used for magnetic storage applications are a field of intense research and development that requires extremely sensitive techniques to estimate device parameters critical for further miniaturization and optimization. Various techniques have been applied for local magnetic characterization, such as spin-polarized scanning electron,¹ Kerr microscopy,² and scanning near-field magneto-optical³ or Lorentz microscopy.⁴ Scanning probe microscopy (SPM) such as magnetic force microscopy (MFM) techniques have been used to characterize surfaces of magnetic storage disks as well as RWHs.^{5,6} For instance, Proksch and co-workers have demonstrated the gigahertz response of recording heads with MFM techniques.⁷ While analyzing an active write element by MFM, which is usually operated in noncontact mode, the high magnetic field generated by the head may attract the tip into contact, or may induce changes in the tip magnetization.⁸ Hence SPM cantilevers with high spring constants have been used for MFM imaging, and high coercivity MFM tips that avoid tip magnetization changes have been fabricated.⁹ Nevertheless, the above-mentioned artifacts may lead to misinterpretation of MFM images. Development of additional SPM techniques using nonmagnetic tips is therefore highly desirable. The technique we developed here takes advantage of the coupling between the magnetic and mechanical properties of magnetic materials, described for example by their magnetostrictive coefficients.

Magnetostrictive materials are used, for example, as powerful transducer systems^{10,11} and as one layer of a spin-valve strain sensor to detect small deflections.¹² The magnetostrictive coefficient is determined from the bending of cantilevers coated on one side with a magnetostrictive layer when they are exposed to varying external magnetic fields¹³

or by a direct measurement of their extension in a known external magnetic field. Such extension measurements have also been performed by means of scanning tunneling microscopy.¹⁴ In addition, scanning force microscopy (SFM) topography data have been used to calculate the magnetostrictive coefficient from surface deformations in Terfenol-D crystals.¹⁵ In this letter we present experimental data of local magnetostriction in a thin layer deposited on the surface of a RWH.

We used a RWH removed from the production line prior to the wear-protection coating process,¹⁶ the geometry and thickness of which are presented as a schematic cross section in Fig. 1(a). The magnetic field emanating from the RWH can be controlled by varying the write coil current I_{RWH} using an external ac current source. Magnetic fields of up to $2.0 \times 10^5 \text{ A m}^{-1}$ can be generated between pole tips P_1 and P_2 . A topographic image recorded by SFM and representative of these microstructures is presented in Fig. 1(b). It clearly displays surface features of both pole tips and the magnetic shielding layers. Topographic variations across the layers are typically in the range from 5 to 10 nm. A 150-nm-thick magnetostrictive film,¹⁸ e.g., Tb-Fe, was deposited on

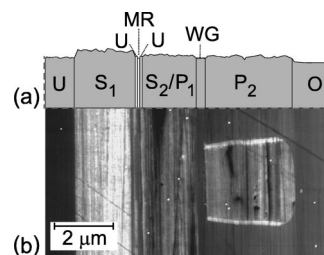


FIG. 1. (a) Sketch of a typical surface corrugation and layering sequence of the characterized RWH. U is the undercoat, S_1 and S_2 are magnetic shields, MR is the magnetoresistive sensor including its wiring, P_1 and P_2 are the magnetic pole tip ends, WG is the writing gap, and O is the overcoat layer. (b) SFM topography of an RWH displayed as a gray-scale image shows typical recession phenomena of such RWH devices (Ref. 17).

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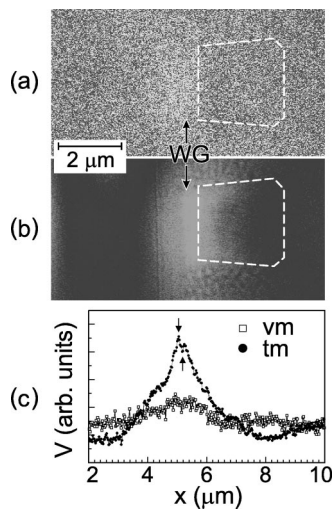


FIG. 2. (a) Vertical response amplitude V_{vm} of the magnetostrictive overcoat of the RWH presented in Fig. 1; identical position and scan size. The response ($I_{RWH}=100$ mA) is encoded in dark (weaker response) and light (stronger response). (b) Torsional response amplitude V_{tm} ($I_{RWH}=100$ mA). In both images, the writing gap is indicated and P_2 's pole tip contour is sketched by a white dashed line. (c) Line scans perpendicular to the layered structure across the WG.

the pole-tip region of the RWH^{10,11} and did not change the topographic surface features significantly.

For this magnetostrictive layer at the saturation magnetic field, a maximal thickness change of only ≈ 0.1 nm is calculated, which superposes surface roughness. From the 16-bit resolution of the analog-to-digital converter we calculated a theoretical vertical piezoresolution on the order of 0.01 nm, which is not convenient for measuring the expected deformation. One way to overcome these limits is to modulate the magnetic field of the RWH by a modulated I_{RWH} ($0 < I_{RWH} < I_{max}$), which results in a periodic deformation of the magnetostrictive thin film. Local deformations of the surface can actuate a laterally scanned force microscope cantilever operated in the contact mode. To measure this actuation, the SFM detector output voltage is referenced to the write coil voltage V_{RWH} in a phase-sensitive amplifier (lock-in). Its output signal, V_{vm} , for the vertical and V_{tm} for the torsional response of the cantilever can then be displayed.

Data of the deflection mode and the torsion mode of the laterally scanned nonmagnetic tip are presented in Figs. 2(a) and 2(b). The maximum response for both modes is located between the two pole tips, which is consistent with magnetic characterizations performed with other techniques.⁶ From the normalized values, the response magnitude in the writing gap (WG) was a factor of ≈ 5 higher in the torsional than in the deflection mode [Fig. 2(c)]. The resolution, estimated from the torsional mode line scan, is ≈ 100 nm, i.e., half the peak-to-valley distance (see arrows). Under our experimental conditions, Tb-Fe films are magnetized out-of-plane at zero magnetic fields. With increasing I_{RWH} a magnetic field in the WG parallel to the surface is generated. In-plane magnetized domains nucleate and 90° domain walls propagate until saturation magnetization is reached, leading to a local extension of the film's dimensions along this direction. For I_{max} used in the experiments presented here the magnetic field in the WG was high enough to reach this state. With decreasing I_{RWH} ,

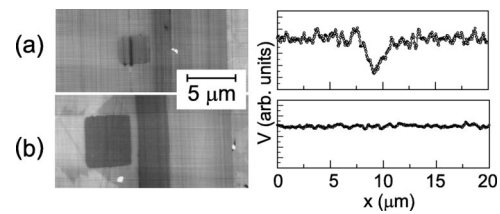


FIG. 3. (Left) SFM topography and (right) magnetostrictive response in the vertical mode, acquired for two different heads with P_2 made of (a) $Ni_{45}Fe_{55}$ permalloy and (b) $Ni_{80}Fe_{20}$ permalloy.

the Tb-Fe film returns to a low remanent magnetization state with out-of-plane magnetization.

Two actuation phenomena may contribute to the observed lateral contrast place: First, adhesion forces may keep the position of the cantilever tip fixed relative to the surface, whereas the film is locally extended. The lateral motion of the surface associated with the rotation of the magnetization at the tip location twists the cantilever, leading to the torsional response. Second, when the tip is not moved with the surface, magnetoacoustic emission coupling into the sensor, owing to 90° domain wall movements during magnetic field switching, might lead to the observed lateral contrast. Near the WG—where the generated magnetic field is too small for in-plane saturation—torsional-mode contrast is observed due to partial rotation of the magnetization at these locations.

To confirm that the observed contrast is not dominated by contributions from thermal expansion or eddy current damping,^{19,20} we performed similar scanning experiments on two uncoated devices. For both devices, P_1 is made of $Ni_{80}Fe_{20}$, which has a magnetostrictive coefficient close to zero, whereas P_2 is made of $Ni_{45}Fe_{55}$ [Fig. 3(a)] or $Ni_{80}Fe_{20}$ [Fig. 3(b)]. $Ni_{45}Fe_{55}$ has a nonzero magnetostrictive coefficient ($\approx 30 \times 10^{-6}$), but both materials have similar thermal expansion coefficients and electrical resistivities. Only for the $Ni_{45}Fe_{55}$ -type head was a weak vertical deflection contrast observed on P_2 (≈ 1 nm). In contrast to the Tb-Fe film experiment, the contrast observed here is not attributed to domain movements, but to different volume magnetostriction in the heads.

To summarize, this technique is able to visualize locally magnetic fields emanating from a RWH device using a magnetostrictive thin film as a sensor between the device and the scanned SFM tip. The lateral resolution of the magnetic field is in the 100 nm realm. The reconstruction of the magnetic field could be simplified by using piezomagnetic layers having a linear response with magnetic fields and/or by more advanced methods to detect cantilever deformations (deflection, twisting, buckling) in all three directions.²¹ Very interesting complementary results, although obtained with other magnetic structures, have been reported recently.²² We foresee that the reported and related techniques can first be used to characterize a wide range of magnetic materials and also for industrial process control. Second, other properties, such as the magnetoelastic and the piezomagnetic effect, can be used in a similar way to infer magnetic characteristics of microstructures or of magnetic multilayers. Third, the sensing layer can be incorporated into the scanned local probe, allowing characterization of the magnetic field at a well-

defined distance. In conclusion, the technique described introduces a way to study magnetostriction effects locally.

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